Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes

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Abstract: Glacier shrinkage is a strong driver of change for mountain hydrology and landscape development and bears multiple risks as well as new options for human livelihoods. In the tropical Andes, current rates of glacier loss are investigated to some point but associated future extent of both vanishing glacier and forming lake areas and volumes are poorly explored. This study combines an analysis of current (1988–2016) and future (2050/2100) glacier and lake development in the Vilcanota-Urubamba basin (Cusco, Southern Peru). Total glacier area (volume) decreased by 37.3% (20.5%) from 226.1 km2 (8.122 km3) in 1988 to 141.7 km2 (6.457 km3) in 2016. Adjacent lakes increased in area (number) by 15.5% (18.3%) from 23.3 km2 (460 lakes) in 1988 to 26.9 km2 (544 lakes) in 2016 while corresponding lake volume has grown by 9.7% from 0.637 km3 to 0.699 km3, respectively. High spatiotemporal variability can be observed in the basin, with strongest glacier shrinkage in the lower lying northwest (Cordilleras Urubamba and Vilcabamba) and highest growth and lake extent in the Altiplano region of the southeast (Cordillera Vilcanota and Quelccaya ice cap). Future glacier areas could substantially decrease between 40.7% (RCP2.6) and 44.9% (RCP8.5) within the next decades (2031–2060) and between 41.4% and 92.7%, respectively, within this century (2071–2100). Hence, Andean landscapes would transform into mostly glacier-free areas with some remaining ice-covered summits over 6000m asl. and this would imply a loss of permanently stored water of several km3. Until the end of this century, important future lake areas could develop and continue to grow between 3.2% (RCP 2.6) and 6.0% (RCP8.5) with an associated volume increase of 0.032 km3 (4.6%) and 0.041 km3 (5.9%), respectively. Our current baseline and future projections suggest that a decrease of glacier shrinkage is also followed by a slowdown in lake formation and particularly volume growth which might have already developed or occur in the near-future. Under the depicted scenarios of change, strong emphasis needs to be promptly put on feasible water management and storage options as robust adaptation measures tackling high uncertainties, risks and complex hydroclimatic and socioenvironmental intertwining.

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Title:

Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes

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Keywords

NDSI, NDWI, tropical glaciers, future mountain landscapes, water management

Highlights

- Glacier areas and associated volumes have substantially decreased
- Lakes have increased in number, area and volume
- Future tropical Andean landscapes could be mostly glacier-free including new lakes
- Point of fastest glacier volume loss and lake volume increase might be reached
- Options for long-term water management of new lakes must be analyzed now

ABSTRACT

Glacier shrinkage is a strong driver of change for mountain hydrology and landscape development and bears multiple risks as well as new options for human livelihoods. In the tropical Andes, current rates of glacier loss are investigated to some point but associated future extent of both vanishing glacier and forming lake areas and volumes are poorly explored. This study combines an analysis of current (1988-2016) and future (2050/2100) glacier and lake development in the Vilcanota-Urubamba basin (Cusco, Southern Peru). Total glacier area (volume) decreased by 37.3% (20.5%) from 226.1 km^2 (8.122 km^3) in 1988 to 141.7 km^2 (6.457 km^3) in 2016. Adjacent lakes increased in area (number) by 15.5% (18.3%) from 23.3 km^2 (460 lakes) in 1988 to 26.9 km^2 (544 lakes) in 2016 while corresponding lake volume has grown by 9.7% from 0.637 km^3 to 0.699 km^3, respectively. High spatiotemporal variability can be observed in the basin, with strongest glacier shrinkage in the lower lying northwest (Cordilleras Urubamba and Vilcabamba) and highest growth and lake extent in the Altiplano region of the southeast (Cordillera Vilcanota and Quelccaya ice cap). Future glacier areas could substantially decrease between 40.7% (RCP2.6) and 44.9% (RCP8.5) within the next decades (2031-2060) and between 41.4% and 92.7%, respectively, within this century (2071-2100). Hence, Andean landscapes would transform into mostly glacier-free areas with some remaining ice-covered summits over ~6000 m asl. and this would imply a loss of permanently stored water of several km^3. Until the end of this century, important future lake areas could develop and continue to grow between 3.2% (RCP 2.6) and 6.0% (RCP8.5) with an associated volume increase of 0.032 km^3 (4.6%) and 0.041 km^3 (5.9%), respectively. Our current baseline and future projections suggest that a decrease of glacier shrinkage is also followed by a slowdown in lake formation and particularly volume growth which might have already developed or occur in the near-future. Under the depicted scenarios of change, strong emphasis needs to be promptly put on feasible water management and storage options as robust adaptation measures tackling high uncertainties, risks and complex hydroclimatic and socioenvironmental intertwining.

1. INTRODUCTION

As with other high mountain regions, the tropical Andes are adversely affected by strong hydroclimatic and socioeconomic impacts in the context of global change (Baraer et al., 2012; Buytaert and De Bièvre, 2012; IPCC, 2014; Urrutia and Vuille, 2009; Vuille et al., 2008a). In the Andes of Peru, allover glacier shrinkage corresponding to an area loss of approximately 43% between 1970 and 2010 (ANA, 2014a), has uncovered many glaciated areas below 5000 m asl. (López-Moreno et al., 2014; Mark and Seltzer, 2005; Rabatel et al., 2013; Salzmann et al., 2013). In combination with permafrost degradation (>5000 m asl.), this development bears multiple consequences, such as emerging hazards from unstable moraines, ice and rocks (Haeberli et al., 2017), changes in erosion and sedimentation rates (López-Moreno et al., 2017), as well as spatiotemporal alterations in both quantity and quality of mountain water resources (Drenkhan et al., 2015; Stark et al., 2012). As a result of glacier shrinkage, many high mountain lakes are currently developing in Peru (Colonia et al., 2017; Drenkhan et al., 2015; Emmer et al., 2016) and other glaciated mountain regions, such as the Alps (Haeberli et al., 2016a) and Himalayas (Gardelle et al., 2011; Kapitsa et al., 2017). These new and growing lakes imply several risks, such as Glacier Lake Outburst Floods (GLOF), water storage potentials as well as open administration and water management questions (Allen et al., 2016; Haeberli et al., 2016a; Terrier et al., 2011). Anticipating both current and future risks as well as new options for water use linked to deglaciation processes and lake formation and growth, are therefore crucial. In the Andes of Peru, glacier lake growth has only been assessed for a few catchments in the Ancash (Santa river) (Emmer et al., 2016) and Cusco (Vilcanota-Urubamba river) (Guardamino and Drenkhan, 2016; Hanshaw and Bookhagen, 2014) regions. A comprehensive lake inventory for all 19 glaciated mountain ranges in Peru was compiled for the period 1970-2010 (ANA, 2014b). Recently, efforts have been made to build a nation-wide inventory of potential future lakes (Colonia et al., 2017) which is about to be published with additional material for stakeholders. This represents a first comprehensive approach for the Peruvian Andes, and, to our knowledge, other tropical mountain regions, to project and quantify future lake development and associated water volumes.

Nonetheless, there are no studies yet which comprehensively assess past, present and future glacier and lake development under scenarios of climate change and which put them into a broader context of future water management. Here, we address this gap by presenting three main aspects for the upper Vilcanota-Urubamba basin (hereafter: 'VUB') in Southern Peru: i) a multi-temporal analysis (1988-2016) of recent glacier and lake development, ii) an assessment of scenario-based future glacier extension and developing lakes until 2050 and 2100, and, iii) related glacier and lake volume estimations. The objective of this study is to identify current and potential future glacier and lakes trend changes and to discuss associated uncertainties. Beyond our study region, the achieved results bear relevance within a global context of glacier shrinkage, lake development and associated challenges and options for long-term risk and water management.

2. REGIONAL SETTING

The study area is situated between the Central and Eastern Andes at the transition towards the Peruvian-Bolivian Altiplano in the region of Cusco, Southern Peru and comprises the entire extent of the upper VUB including the Vilcanota-Urubamba rivers (*Fig. 1*). We defined the outlet of the basin around 400 km northwest from its origin at Abra La Raya (5443 m asl.), where the Huamanmarca tributary diverts into the Upper Urubamba river at Santa María (1180 m asl.). The whole basin area covers 11,048 km² and includes a large glacier extent of, listed in downstream running order, the Cordillera Vilcanota (66.0 km²), Quelccaya ice cap (18.4 km²), Cordillera Urubamba (18.1 km²) and Cordillera Vilcabamba (39.2 km²). The southernmost glacier fragment corresponds to Cordillera La Raya, but due to its insignificance as mountain range in the basin (total area <2 km²) it has been considered as part of the Cordillera Vilcanota. Total glacier area fraction in the VUB is about 1.3% which strongly varies at catchment scale from 0% to 5.5%.

The complex topographic and hydroclimatic situation of the study area is characterized by outer- and subtropical features including strong westerlies during the pronounced dry season (austral winter) and prevailing easterlies transporting moisture during the wet season (austral summer) (Garreaud et al., 2009; Salzmann et al., 2013). The region is particularly influenced by interannual anomalies of El Niño Southern Oscillation (ENSO) with increased easterly moisture transport during El Niño and with enhanced dry westerly flow regimes during La Niña (Perry et al., 2014). These anomalies have an impact in glacier mass balance in the Peruvian Andes with potentially strong melting due to enhanced ablation during El Niño and more stable or even positive mass balance during La Niña. Nonetheless, ENSO signal and magnitude on glaciers are not always clear and discriminable from other important climatic features (cf. Vuille et al., 2008b). However, for the upper VUB and within our study period, Thompson et al. (2017) identified a consistent relationship of negative mass balance related to e. g. the last El Niño 2015/16. Generally, positive temperature trends at a magnitude of approximately 0.1-0.4°C/decade (1965-2009) are observed in the VUB from both station (SENAMHI, 2009) and NCEP/NCAR reanalysis data (Salzmann et al., 2013). In the same period, precipitation series also indicate (slightly) positive values in the order of 0.2-2.2 mm/year but particularly from the 2000s a decrease of this trend has been observed (Avalos et al., 2012) which was partially confirmed by (Salzmann et al., 2013). This could already be an indicator for a future 'aridification' of the Altiplano and, hence, the VUB which was also described by the IPCC (2014). Additionally, Neukom et al. (2015) found potential precipitation reductions in the order of 19-33% during the wet season in austral summer (DJF) until 2100.

In the VUB, rural communities prevail with traditional livelihoods, mostly low socioeconomic and high poverty levels (INEI, 2017a) and, hence, high vulnerabilities towards adverse effects of climate change (Buytaert et al., 2017; Orlowsky et al., 2016; Postigo et al., 2008). Glaciers represent an important cultural value within the indigenous Andean cosmovision (Bolin, 2009; Drenkhan et al., 2015) including mountain deities, offerings and pilgrimage activities. The above mentioned changes in the climatic regime would severely affect glaciers and livelihoods for the majority of 838,500 people inhabiting the VUB (INEI, 2017b), by combining long-term effects of less accumulation and enhanced ablation rates (Kronenberg et al., 2016). With a total area of ~260 km², the Cordillera Vilcanota includes the second-largest tropical glacier extent worldwide and provides crucial water supply for multiple water users and ecosystem services. Continued glacier shrinkage coupled with growing irrigated agriculture (currently more than 2087 km²) and hydropower demand (more than 290 MW installed capacity) might therefore strongly affect water availability for socioenvironmental systems, particularly in the dry season and upstream areas (Drenkhan et al., 2015; INEI, 2013; Kronenberg et al., 2016; Orlowsky et al., 2016). Furthermore, landslides and GLOF can pose severe risks for local livelihoods and the sensitive tourism sector (Cusco and Machu Picchu) including losses of infrastructure and lives. Large GLOF events at Salcantay-Yanatile/Santa Teresa (Cordillera Vilcabamba) in 1996/1998 (Carlotto et al., 2007; Frey et al., 2016) or at Chicon-Urubamba (Cordillera Urubamba) in 2010 (Portocarrero, 2014) illustrate their damage potential. On the other hand, rapid changes in this high mountain environment also bear some new options and co-benefits as new lakes could be used for local water storage, as tourism attractions as well as additional routes for Andean mountaineering in recently deglaciated areas (Vuille et al., 2017).

Nonetheless, data about current glacier shrinkage, related processes and risks are scarce in the region. Only a few studies have quantified multi-temporal glacier shrinkage for (parts) of the Cordillera Vilcanota (Hanshaw and Bookhagen, 2014; Salzmann et al., 2013; Veettil et al., 2017; Veettil and de Souza, 2017) and Vilcabamba (Guardamino and Drenkhan, 2016), some of them including lakes assessments. The Glaciology and Water Resources Unit (UGRH) of the National Water Authority (ANA) in Peru has compiled comprehensive inventories of glacier and lake extents for the Cordilleras Vilcanota, Urubamba and Vilcabamba until 2009 (ANA, 2014b, 2014a) which are currently updated. The recent inventory of future lakes under the scenario of overall disappearance of Peruvian glaciers by Colonia et al. (2017) is particularly important for both future risk and water management assessments.

3. DATA AND METHODS

This study uses free multi-spectral optical satellite data from five points in time between 1988 and 2016, separated by 6-year intervals (except for 1988-1998). Therefore, radiometrically and geometrically corrected L1T and L1C products from Landsat 5 TM (1988, 1998, 2004 and 2010) and Sentinel-2 MSI (2016) were downloaded from USGS Earth Explorer and ESA Copernicus Open Access Hub, respectively (*Tab. 1*). All scenes were acquired in the dry season between June and September (austral winter) in order to minimize potential misclassification due to temporal snow cover. Generally, temporal snow cover extent is low or negligible in tropical glacier areas and therefore less determinant for a correct ice classification, only in the scenes 2004-2016 limited snow cover is present in some regions. Digital Elevation Model (DEM) data comes from an adapted version of the global Shuttle Radar Topographic Mission (SRTM) 1° provided by Alaska Satellite Facility (ASF), University of Alaska

Fairbanks which was developed for ALOS PALSAR imagery correction. This DEM (hereafter: 'SRTM AP') is freely distributed since 2015, artifact- and void-corrected and upscaled from originally 30 m to 12.5 m spatial resolution (ASF, 2015). Accuracy has not been specifically assessed but probably lies within the order of the source SRTM 30 m with ≤ 16 m absolute vertical and ≤ 20 m absolute horizontal circular accuracy.

3.1 Glacier mapping

For the Landsat 5 and Sentinel-2 scenes, semi-automatic glacier area mapping was applied using the Normalized Difference Snow Index (NDSI), which represents an effective and widely used band ratio to detect and discriminate snow and ice (Hall et al., 1995; Paul and Kääb, 2005; Salzmann et al., 2013; Sidjak and Wheate, 1999; Silverio and Jaquet, 2005). Therefore, the green band (Landsat 5: band 2, Sentinel-2: band 3) of high reflectivity and short-wave infrared band (bands 5 and 11, respectively) of low reflectivity of ice were used. For the Sentinel-2 scene, a bilinear resampling of band 11 from 20 m to 10 m spatial resolution was applied. Considering the different spectral and radiometric resolutions of Landsat 5 and Sentinel-2, NDSI thresholds of both satellite products had to be adapted for adequate ice discrimination. Additionally, a blue band shadow cast correction (Paul et al., 2011; Paul and Kääb, 2005) using a minimum DN threshold of 31-46 (Landsat 5) and 500-700 (Sentinel-2) was applied. For more information on the imagery and applied thresholds see *Tab. 1*.

For both band ratios, results are quite robust but manual editing is necessary in order to merge or discard residual areas, eliminate cases of confusion (e. g. with clouds, water bodies) and add shaded or debris-covered glacier areas. First, glacier fragments were filtered using a minimum surface threshold of ≥ 5400 m² (= 6 Landsat 5 and 54 Sentinel-2 pixels), similar to the Peruvian inventory of glaciers which uses a value ≥ 5000 m² (ANA 2014). Shadowed glacier areas were then identified with a hillshade map computed from SRTM AP using the corresponding sun angle and azimuth of the satellite scene (Frey and Paul, 2012). Additionally, automatic masking-out of misclassified lakes as glacier areas was performed by adding a Normalized Difference Water Index (NDWI) layer (*section 3.2*).

In a last step, corresponding glacier and water volume were computed based on ice-thickness calculations with the Glacier bed Topography (GlabTop) model (*section 3.4*). Therefore, all glacier outlines 1988-2016 were intersected with the SRTM AP and ice volume was then calculated pixel-by-pixel subtracting the 1988 bed topography (= no glaciers) from 1988-2016 (= glacier extent of each specific year). Finally, the corresponding water volume was determined assuming mean ice density of 900 kg/m^3 over the entire glacier.

3.2 Lake mapping

For the Landsat 5 and Sentinel-2 scenes semi-automatic lake area mapping was performed using the NDWI, which represents a robust and frequently used band ratio to discriminate water bodies (Huggel et al., 2002). Therefore, the near infrared band (Landsat 5: band 4, Sentinel-2: band 8) of low reflectivity and blue band (Landsat 5: band 1, Sentinel-2: band 2) of high reflectivity of water were used. Different thresholds were applied according to three main lake reflectance types: low-reflecting (A), high-reflecting (B) and vegetation-influenced (C) lakes. For further information on the individual NDWI thresholds applied, see *Tab. 1*. In this study, lakes were defined by minimum area ($\geq$ 2700 m^2, corresponding to 3 Landsat 5 and 27 Sentinel-2 pixels) and minimum altitude ($\geq$ 4000 m asl.) thresholds. Additionally, a slope map helped to detect potential lake areas depending on the DEM input with the SRTM AP performing well for small and medium lakes in a rough topography ($\leq$ 15°) and the coarser global SRTM 3° (90 m) for medium and large lakes in a smooth relieve ($\leq$ 10°). For the purpose of this study, the two largest reservoirs Langui Layo (4002 m asl., ~55 km^2, usable volume: ~0.020 km^3) and Sibinacocha (4917 m asl., ~28 km^2, usable volume: ~0.110 km^3) were excluded from our analysis, as they are manually controlled and in order not to distort the statistics. Only the two reservoirs combined, correspond for about 76% of total lake area above 4000 m asl. in the VUB.

No systematic bathymetry measurements have been performed in the VUB and adjacent regions. Considering that access to the mostly remote lakes is limited and no reliable technique is available which allows to determine lake depth and corresponding water volume from satellite imagery (Cook and

Quincey, 2015), other (empirical) alternatives must be included. Here, we apply the empirical area-depth relationship from (Huggel et al., 2002) which is defined as

$$D = 0.104\ A^{0.42}$$

where D = mean depth (assuming regular lake-bottom topography) and A = lake area which includes a fixed exponent defined from regression analysis for bathymetries of 15 analyzed lakes in different high mountain regions. Corresponding water volume was computed for each lake in the period 1988-2016 by multiplication of the mapped area assuming that mean depth is representative neglecting further lake topography variability as well as sedimentation processes.

3.3 Future glacier development

The estimation of potential glacier extent is based on the IPCC AR5 Representative Concentration Pathways (RCP) scenarios (IPCC, 2013). We are focusing on the low greenhouse-gas (GHG) concentration RCP2.6 and the high GHG concentration RCP8.5 in order to cover the whole range of possible climate future trajectories. The RCP2.6 underlies a peak in radiative forcing at ~3.1 W/m² before 2050 and decline towards 2.6 W/m² until 2100, while RCP8.5 implies increasingly strong rising of radiative forcing to ~4.6 W/m² in 2050 and 8.5 W/m² in 2100 (cf. Van Vuuren et al., 2011). We used mean monthly near-surface air temperature (TAS) data of the multi-ensemble Coupled Model Intercomparison Project Phase 5 (CMIP5) which includes global climate models. CMIP5 is a collaborative climate modelling process coordinated by the World Climate Research Programme (WCRP) and is used in the IPCC AR5 as a basis for the comprehension of climate change impacts and future projections (Taylor et al., 2012). Here, monthly CMIP5 RCP scenario runs were derived from the Royal Netherlands Meteorological Institute's (KNMI) Climate Explorer, for more information see *https://climexp.knmi.nl/*. For our study region (defined as grid between 73.5-70.0°W and 12.5-15.0°S), the baseline temperature was computed for the 1981-2010 mean. Further mean temperature rise in the 21st century for RCP2.6 and RCP8.5 with regard to the baseline period, corresponds to +1.2°C and +2.0°C, respectively, until the 2050 time window (2031-2060 mean) and +1.2°C and +4.3°C, respectively, until 2100 (2071-2100 mean), see *Tab. 6*.

Future glacier areas were then delimited by Freezing Level Height (FLH) estimations using the RCP scenarios and a base altitude of 5010 m asl. This approach is used by Schauwecker et al. (2017) who calculated current and future FLH levels for the Cordillera Vilcanota based on climate reanalysis, satellite and station data and confirm that wet season (DJF) FLH accounts for a reasonable approximation for current and future lower most glacier elevations. For future FLHs under RCP2.6 and RCP8.5 conditions until 2050 and 2100, a constant mean inversed lapse rate of 150m/1°C was used. Corresponding water volume was calculated with GlabTop's pixel-by-pixel bed topography calculation with an adapted mean ice density of 800 kg/m³ considering that the remaining future glacier extent would mostly be steep, thin and the firn-ice transition close to the bedrock.

3.4 Future lake development

Future lakes were modeled with the GlabTop tool which was developed by Linsbauer et al. (2009) and Paul and Linsbauer (2012) using glacier and lake data from the Alps. Based on a simple empirical parameterization scheme with underlying complex glacier mechanics (Haeberli and Hoelzle, 1995), this tool calculates, in combination with basic glacier and elevation data, ice-thickness distribution along multiple flowlines of glaciers ('branch lines'). Hence, this allows to model bed topography (= terrain without glaciers) and overdeepenings (= depressions) in the glacier bed which can later be selected as locations of potential future lakes under scenarios of deglaciation (Linsbauer et al., 2012).

The required glacier and elevation dataset consists of i) glacier outlines, ii) branch lines, and, iii) a DEM. We used the glacier outlines from 2016 mapped from Sentinel-2 data (*section 3.1*) and manually digitized branch lines along multiple flow lines (perpendicular to the contour lines) which were created each 100-300 m of glacier width. Elevation data was taken from the SRTM AP. Furthermore, we only considered overdeepenings with a minimum area of 2700 m² as sites with potential future lake formation. GlabTop was originally developed for the Alps and there are no further applications for the tropical Andes, except the recent study by Colonia et al. (2017). The fact that the tropical Andean and, hence, VUB glaciers show a different mountain-slope morphology with less flat and large valley glaciers than the Alps, could require some adjustments of the model. In order to gain insight into the modeling dependence on the shape factor (referring to the cross-sectional form of the valley), we analyzed different test sample runs. Therefore, the default shape factor f (0.80), a lower f (0.65) and higher f (0.95) were selected using 1988 as baseline in order to compare modeled 'future' with actually existing lakes in 2016. For more information on the shape factor assumptions see Nye (1965).

Particularly at the glacier terminus, apparently large overdeepenings and, thus, future lakes might be modelled due to spatial inconsistencies of the ice thickness calculated at the lowermost end of the branch line and ice thickness of 0 m at the glacier terminus (Frey et al., 2014), see *section 5.2*. In order to preclude these sites and other potential errors, a semi-automatic ranked confidence approach based on glacier morphology criteria was used, similar to other studies (Colonia et al., 2017; Frey et al., 2010; Haeberli et al., 2016b). Therefore, we defined an overall excluding criterion for glacier area with a slope of ≤ 5°. A 3-by-3 cell low-pass filtering (smoothing) was applied to the SRTM AP and lake areas ≥ 2500 m² (= 16 DEM pixels) were selected.

Then the following morphological criteria were applied to the current glacier surface characteristics and geometry i) downslope (priority) and upslope increase of surface slope, ii) lateral glacier narrowing, and, iii) heavily crevassed areas following a crevasse-free zone. Each criterion was rated by allocating 0-2 points (0 = criterion not visible, and 2 = criterion applies clearly), thus each lake was rated with 0 = no, and 6 = best conditions for potential lake development. In parallel, a visual interpretation of high-resolution imagery from Google Earth and the low-pass filtered map with critical slope classes (0-2° for debris-covered glaciers, 2-5° as maximum lake slope criterion, etc.) helped to control the somehow subjective definition of index-ranking.

Locations which met the criteria of glacier surface slope ≤ 5° and a total of ≥ 3 out of 6 possible points (= at least two out of three criteria are fulfilled) were selected as significant localities with overdeepenings in the glacier bed, and therefore, a potential for future lake formation. In a last step, these sites were intersected with the future glacier extent in order to gain a better spatiotemporal understanding of future lake development within the 21st century (2050/2100) according to two RCP scenarios (*section 3.3*). Scenario-based future lake areas and volumes were computed, the latter derived from GlabTop's bed topography using the adapted mean ice density of 800 kg/m³.

4. RESULTS

4.1 Glacier and lake changes (1988-2016)

In the study period, glacier areas have substantially decreased by 37.3% from 226.1 km² in 1988 to 141.7 km² in 2016, see *Tab. 2*. This corresponds to an annual average loss of 1.3% which is comparable to other studies in the Vilcanota-Urubamba region, such as Veettil and de Souza (2017) with 1.2%/year for 1975-2015 and Hanshaw and Bookhagen (2014) with 1.4%/year for 1988-2010. Our results are slightly lower than those of Salzmann et al. (2013) who calculated 1.6%/year for 1985-2006 in the Cordillera Vilcanota and above the average of the National Glacier Inventory for whole Peru (1.1%/year for 1970-2010) (ANA, 2014a). Overall glacier shrinkage is clearly detectable for the whole study period and for all four mountain ranges (*Tab. 3*), apparently with a decreasing trend which is only interrupted by an intense melt period 2004-2010 and a subsequent strong slowdown. This general deceleration trend of retreat has also been confirmed for the 1996-2006 period in the Cordillera Vilcanota by Salzmann et al. (2013) and for the 2010-2014 period in the Cordillera Vilcabamba by Guardamino and Drenkhan (2016). At the same time, glacier volume has decreased to a lower extent, by 20.5% from 8.122 km³ in 1988 to 6.457 km³ in 2016. Total annual average volume loss corresponds to 0.7% with a clear increasing trend for 1988-2010 (from 0.6%/year to 1.2%/year) and a drop in 2016 (0.9%/year).

Nonetheless, the rate of loss for both glacier area and volume is not uniform in the VUB. A closer look into the spatiotemporal distribution of shrinkage depicts a more heterogeneous picture of the different mountain ranges (*Fig. 2a, Tab. 3*). For the whole study period 1988-2016, the lower-lying northwestern fragment of Urubamba and Vilcabamba (hereafter: 'NWF') at an average altitude of 5109 m asl. indicates a more pronounced area (volume) loss of 1.9%/year (1.1%/year) than the on average 300 m higher situated southeastern fragment of Vilcanota and Quelccaya (hereafter: 'SEF') with 1.2%/year (0.6%/year). At the same time, the NWF is also affected by higher vertical increase of the ablation area which is defined by the glacier's terminus (H_{min}) and the Equilibrium Line Altitude (ELA), here approximated with the mean glacier altitude (H_{mean}) according to statistical and mass balance modeling analysis of Haeberli and Hoelzle (1995), Braithwaite and Raper (2009) and Machguth et al. (2012), see *Fig. 2b*. While in the NWF mean H_{mean} has risen about 75 m and mean H_{min} ascended 152 m, the average increase for the SEF corresponds to 46 m (H_{mean}) and 92 m (H_{min}). For a more detailed analysis based on each period and mountain range see *Tab. 4*.

Lakes have increased in both area and number by 15.5% and 18.3%, respectively, from 23.3 km² (460 lakes) in 1988 to 26.9 km² (544 lakes) in 2016 (*Tab. 5*). This corresponds to an annual average growth of 0.6% and 0.7%, respectively. Also, considerable variability of growth can be observed for the five studied time windows with a strong area increase of 0.4%/year (1998-2004) to 1.4%/year (2010-2016). Lake amount changes are subject to stronger variability which is also linked to temporal drying of some small lakes. A total of 39 temporal lakes (i. e. not present in all study periods) could be identified with a negligible total area of 0.46 km², most of them situated in the SEF (36 lakes), particularly in the high plateau around Lake Sibinacocha (28 lakes). A comparison of both glacier and lake area change and corresponding trend rates for the whole study period is drawn in *Fig. 3*. A thorough analysis of mapped lakes according to their size and altitude (400 m intervals) reveals that particularly small and intermediate lakes (2700-30,000 m²) in the near-periglacial and currently deglaciating zones (4400-5200 m asl.) are dominating (*Fig. 4*). Interesting in this context is the spatio-temporal distribution of change. Total lake number within the smallest area class (2700-5000 m²) has increased in 1988-2010 and decreased in 2010-2016. Both trends can also be observed for the two lower altitudinal zones but not for 4800-5200 m asl. where the decline starts already in 2004, and for 5200-5600 m asl. where new lakes have formed since 2010. Total lake number of the next larger area classes (5000-30,000 m²) has generally increased with strongest growth of the larger lakes (10,000-30,000 m²) particularly in the zone 4800-5200 m asl. The described trends suggest strongest change in the currently deglaciating zone (4800-5200 m asl.) while, below that altitude, new lakes are (nearly) not forming anymore and previously small lakes have reached considerable sizes over 10,000 m².

Lake volume has increased by 9.7% from 0.627 km³ in 2004 to 0.699 km³ in 2016 but the time window 1998-2004 shows a negative trend (-0.4%/year) which is associated with slightly reduced lake area in the same period. Total annual average volume growth is about 0.4% with an increasing trend for 1998-2010 (0.3%/year to 1.0%/year) and a drop in 2016 (0.9%/year).

4.2 Future glacier development (2016-2050/2100)

Future glacier areas could substantially decrease between 40.7% (RCP 2.6) and 44.9% (RCP8.5) from current levels (2016) towards 2050 (2031-2060 mean). Until 2100 (2071-2100 mean) the corresponding shrinkage could be between 41.4% (RCP2.6) and 92.7% (RCP8.5), see *Tab. 6 and Fig. 5*. Hence, while the impact of different emission and climate scenarios on glacier shrinkage is yet moderate for the mid-21st century, it becomes very significant towards the end of the century. A high-emission scenario (i. e. RCP8.5) implies a virtually complete loss of glaciers whereas a low-emission scenario (i. e. RCP2.6) allows conservation of nearly 60% of glacier areas and related volumes until 2100. These calculations are based on the FLH estimations defining the glacier terminus at 5276 m asl. (5307 m asl.) for RCP 2.6 (RCP8.5) until 2050 and 5281 m asl. (5647 m asl.) for RCP 2.6 (RCP8.5) until 2050. Our results are at the lower limit of the estimations from Schauwecker et al. (2017) who determine the terminus at 5320 m asl. ± 190 m (5940 m asl. ± 390 m) for RCP2.6 (RCP8.5) for the Cordillera Vilcanota only. Our FLH estimations depend on the climatic dataset, current FLH values adapted from Schauwecker et al. (2017) and a constant inversed lapse rate. For a more detailed discussion see *section 5.2*.

4.3 Future glacier lake development (2016-2050/2100)

Due to the underlying different valley geometries in the Andes, we compared different model runs with the default shape factor f (0.80) for the 1988 baseline (*section 3.4*). The lower f (0.65) led to a larger potential lake extent (+36.1% area and +58.5% volume) and more small residuals, particularly on higher located glaciated areas, most of them not detected in the current glacier inventory of 2016. A higher f (0.95) generated smaller and less lake bodies (-21.6% area and -30.2% volume), which in part matched with actually existing lakes. The same test samples for 2016 led to similar results with an increase of lake area (volume) of 38.6% (65.6%) for f (0.65) and decrease of lake area (volume) of 24.5% (35.8%) for f (0.95). Actually, these test sample runs confirm that the selection of the shape factor might considerably influence lake area and volume estimations. Nonetheless, the locations of the modeled overdeepenings and, hence, potential future lakes, do not vary much for the larger lakes. Therefore, the adaptive approach was dismissed maintaining the default *f* (0.8). Additionally, strong regional differences could be observed for all test samples uniformly, possibly linked to the general valley and glacier morphology. While several modeled lakes in the Quelccaya ice cap (*Fig. 5*) which is characterized by larger glacier tongues and lower overall slopes, have developed until 2016, less lakes were 'correctly' modelled for other steeper glaciers of e. g. the Cordilleras Urubamba or Vilcabamba.

Out of 219 depressions in the glacier beds identified by GlabTop, 49 sites met the criterion of a current glacier slope ≤5° from which 20 were finally selected as locations with potential future lake formation, following the index-based confidence ranking procedure of morphological criteria of glacier surface characteristics (*section 3.4*). Total lake areas would continue to grow in the future by between 3.2% (RCP 2.6) and 4.0% (RCP8.5) from current levels (2016) to 2050. Until 2100 the corresponding area increase could be between 3.2% (RCP2.6) and, more pronounced, 6.0% (RCP8.5). Total water volume of future lakes would potentially increase from currently 0.6991 km^3 by between 0.032 km^3 (RCP2.6) and 0.041 km^3 (RCP8.5) until 2100.

Despite ongoing glacier shrinkage and lake growth, the volume and number of lakes do not strongly increase (anymore). Growth rates would be even higher for the next decades (2050) than by 2100. In the period 2016-2050, lake volume and lake number could on average increase by 0.15%/year and 0.09%/year while until the end of the century a slowdown would set on accounting for 0.07%/year and 0.04%/year, respectively (*Tab. 7*). This could mean that most important, i. e. huge, new lakes are those which already exist or are under development within the next few decades, mostly situated in the low-lying and, thus, flatter mountain slopes. For a more detailed discussion see *section 5.2*.

5. DISCUSSION

5.1 Current trends and uncertainties

The combined semi-automatic glacier classification approach with manual revision using additional high-resolution imagery enabled a quite robust discrimination of glacier areas. In general terms, the error in mapping glaciers with a semi-automatic NDSI approach was estimated at ±5% by Paul and Kääb (2005). Nonetheless, temporal snow cover was found in the years 2016 and, in a lower extent, in 2010 and 2004, which, thus, might have led to some potential misclassification and slightly increases the total error (in the order of a few percent).

The detected overall glacier shrinkage between 1988 and 2016 shows more complex patterns at a detailed spatiotemporal scale (*section 4.1*). Interesting in this context is the around 60% stronger rise of H_{mean} and H_{min} as well as accelerated shrinking of the NWF in comparison with the SEF. Considering this trend difference and projected future rise of H_{min} and H_{mean} (*section 4.2*), the Cordillera Urubamba (highest peak: Sahuasiray, 5818 m asl.) could be the first mountain range in the VUB (nearly) completely free of glacier cover within this century, later followed by the Cordillera Vilcabamba (Salcantay, 6271 m asl.) and the slower deglaciating Quelccaya ice cap (5670 m asl.) and Cordillera Vilcanota (Ausangate, 6372 m asl.). Generally, the NWF could be more affected by current air temperature rise and the ascent of the 0°C-isotherme as its terrain is on average 300 m lower than the SEF. Furthermore, local climatic effects could play a role considering that the NWF is situated at the transition towards the Eastern Cordillera and the SEF belongs to the drier Altiplano region of the Central Andes. The NWF is particularly influenced by moisture transport from the Amazon basin and, given its lower lying glacier extent, could be stronger affected by liquid precipitation over the ablation area in future (cf. Perry et al., 2017). The SEF could be potentially affected by future aridification (IPCC, 2014; Neukom et al., 2015). However, more research is needed to understand climatic drivers and potential future impacts in the different mountain ranges.

Additionally, glacier morphology is different in both regions with a more pronounced steep slope and narrow mountain topography with thinner glaciers in the NWF and prevailing flat tongues with wide valley floors, a reduced vertical glacier extent and thicker glacier bodies in the SEF. These aspects could also influence the dynamic response time of each glacier adjusting its geometry to the respective climatic conditions over time (Jóhannesson et al., 1989). The resulting time lag can be estimated as a function of maximum glacier thickness (at the central flowline) and annual mass balance at the terminus (Haeberli and Hoelzle, 1995). Experiences in the tropical Andes indicate glacier response times of only several years for steep mountain glaciers, such as in the NWF, to a few decades for valley glaciers (Colonia et al., 2017; Salzmann et al., 2013; Schauwecker et al., 2014) which can be more typically found in the SEF. The general decelerating shrinkage trend in all four analyzed mountain ranges, particularly during the last six years, could therefore match with the temperature slowdown of global warming which is also described for the Andes between 1997/98 and 2016 (Vuille et al., 2015). This means that (some of) the VUB glaciers, could have reached or soon be in a phase of adjustment (i. e. decelerated shrinkage) to the climatic conditions at the turn of the 20^{th} and 21^{st} century (cf. Colonia et al., 2017). Another important aspect is to consider superimposed oceanic-atmospheric anomalies additionally impacting these trends, such as ENSO. For instance, our study period includes the last strong El Niño events 1991/92, 1997/98, 2009/10 and 2015/16. However, direct impacts on our observed rates of glacier shrinkage and lake development cannot be clearly attributed with the applied 6-year-observation intervals. Additionally, as stated above, glacier response time is delayed and, thus, a linear interpretation of annual glacier and lake extent changes might be misleading. In summary, more research including larger and more detailed datasets is needed in order to understand and possibly confirm local climatic and morphological effects on potential mid- to long-term changes in glacier shrinkage trends.

Lakes were discriminated with a combined NDWI and slope map approach (SRTM AP and 3°) which led to reasonable results. Some confusions arose from shadows and aquatic vegetation cover variability limiting the water body definition which was manually corrected and substantially reduced misclassifications. A particular observation was the temporal drying of small lakes in the Altiplano region south of Lake Sibinacocha, particularly in the period 1998-2010. These small lakes (<0.02 km^2 on average) seem to be mostly rain-fed and, hence, their size oscillates with interannual precipitation and evaporation variability. This phenomenon had influence on e. g. lake number statistics but was negligible for general area trend detection. While the total amount of lake area, volume and number is increasing, the spatiotemporal distribution is changing. A shift of growth from smallest (2700-5000 m^2) to mid-sized and larger lakes (5000-200,000 m^2) can be observed in the altitudinal zones 4400-5200 m^2 over the whole study period while only small lakes are forming in the highest zone 5200-5600 m asl. where glacier shrinkage is currently initiating. Further research is needed addressing the question if these lakes are growing in the same manner or remaining small due to changes in slope topography and sedimentation rates.

The volumetric estimations of both glacier and lake mass involve larger uncertainties than the area calculations. For example, changes in glacier volume due to surface lowering cannot be detected and quantified with our approach using only the SRTM AP from 2000. In order to calculate consistent multitemporal series of glacier volume, the 1988 bed topography (= largest glacier cover in the study period) has been used for all five time windows and the corresponding glacier area extent. Nonetheless, the results might be overestimated as the SRTM AP used here was taken 12 years after, in 2000. A comparison with calculated volume using the bed topography of the closest observation year (1998: 6.745 km^3) reveals an overestimation of ~14% (0.927 km^3) in comparison to the same year of our results based on the 1988 bed topography. The best way to avoid mentioned inconsistencies and reduce some uncertainty would be the use of individual DEMs for each corresponding observation year which were not acquired for the present study. Area-volume relationships (Bahr et al., 1997) have been extensively applied in past studies featuring apparently high correlation coefficients but actually imply autocorrelation, as area is also part of compared volume and real correlation is, thus, much weaker (Cook and Quincey, 2015). A more thorough and critical discussion has been provided by Haeberli (2016). The empirical area-depth relationship approach (Huggel et al., 2002) applied here for lakes, has also been widely used in the literature (Allen et al., 2016; Bolch et al., 2012) and critically evaluated. Cook and Quincey (2015) confirm that it gives reasonable size of mean depth and lake volume while in some particular cases, such as supraglacial lakes, more complex bathymetries and deglaciated dammed valleys corresponding volumes could be strongly over- or underestimated with errors between 50% and 400%. For the VUB no bathymetry datasets exist which would directly allow us to assess the magnitude of error on our estimations. A proper comparison of area-depth and volume relationships used here with bathymetries taken from 137 lakes mostly situated in the Cordillera Blanca between 2004 and 2013 (UGRH 2014), gives an uncertainty range between ±33% (depth) and ±51% (volume). This confirms at least the relative robustness and suitability of our approach. Nonetheless, high uncertainty resulting from extreme morphometric variability of potential overdeepenings and in several cases insignificant correlation between depth, area, length and width (Haeberli et al., 2016b) makes it impossible to work with precision. In conclusion, the applied method provides a first-order assessment of depth and volume, with higher accuracy required for precise water storage and distribution questions, such as for domestic, irrigation and hydropower demand. Furthermore, for a more realistic picture of current and future lake volumes, a non-regular, complex bed topography as well as sedimentation processes in combination with deglaciation, erosion and evaporation processes need to be considered. These aspects are difficult to assess only with remote sensing techniques and are out of scope of this study.

Finally, an interesting observation represents the fact that while the trend of glacier shrinkage and lake growth continues, the related volumes show a slower decreasing (for glaciers) and increasing (for lakes) trend at both scales, the whole basin (*Tab. 2, Tab. 5*) and different mountain ranges (*Tab. 3*). The possible slowdown is mostly observable in the current period 2010-2016. This might be a first indicator for reaching peak volume change, a tipping point from where on a lower amount of water release from heavily shrunk glacier extent can be naturally stored in adjacent lakes, also driven by changing geomorphology. In other words, while the huge glacier tongues will have mostly vanished in the (near) future, the remaining steeper and thinner mountain glaciers have a lower ice depth and, consequently, store smaller ice and water volumes. Towards the glaciated mountain summits, an increasingly steep topography does not allow anymore for the formation of larger new lakes. Nonetheless, the volume estimations must be taken with caution due to high uncertainties and further research is needed to provide more (in-situ) evidence on long-term trends for the possible peak volume change suggested here.

5.2 Future trends and uncertainties

The simulation of future glacier extent at basin and mountain range scale reveals that many glaciers would lose an important part of their current ice and water content within the next decades. The most ambitious climate policy and mitigation scenario RCP2.6 used here, implies a stabilization of global temperature increase (relative to pre-industrial levels) to 1.7°C until 2100. This is quite in line with the mitigation targets of the Paris Agreement, however, glacier area and volume in the VUB would be reduced in about 40% of current levels. With the non-mitigation ‘business-as-usual’ scenario RCP8.5, glaciers would drastically lose over 90% of their current extent. This means, that until the end of this century glaciers might have nearly or completely disappeared, only the highest summits located above ~6000 m asl. would persist for a longer period, likely even beyond this century.

The FLHs do not directly determine glacier outlines but were described to serve as a good approximation for the lower-most extent of glaciers (Schauwecker et al., 2017), also considering that tropical glaciers have reduced ablation areas (Kaser and Osmaston, 2002). Furthermore, with a projected enhanced air moisture content in high altitudes (Bradley et al., 2006) it would be likely that the atmospheric lapse rate reduces which in turn could exacerbate atmospheric warming (Vuille et al., 2015). Hence, the accelerated temperature rise in high altitudes would force a stronger increase of future FLHs and corresponding lower-most glacier elevations in the Andean region. This gradual effect has not been considered in the present study due to high uncertainty in the context of a complex interplay of different climatic drivers.

For future glacier modeling, some additional considerations of glacier geometry changes and potential cascading effects could be incorporated. Increasingly smaller glaciers have a decreasing ratio of area vs. perimeter which could increase its rate of shrinkage. Furthermore, the strong increase of H_{min} will rapidly reduce the vertical extent of current (typically small) ablation areas, and a further rise of the 0°C-isotherme and ELA is gradually depleting total snow accumulation in the near-future. Additionally, the role of glacier response times must be considered. As response of the warming hiatus until 2016, near-future glacier shrinkage could possibly be attenuated, at least for some years of glacier adjustment (*section 5.1*).

The applied approach for future glacier lake modeling also entails different uncertainties. Based on an uncertainty range of ±30% of ice thickness determined for GlabTop for the European Alps (Linsbauer et al., 2012; Paul and Linsbauer, 2012), we can assume that the ice-depth estimates applied in this study are quite robust and the model's predictive quality is comparable to more complex methods (Farinotti et al., 2017) while its simplicity and rapid calculation are major advantages (Paul and Linsbauer, 2012). A particular problem remains that GlabTop tends to overestimate glacier thickness at the glacier terminus as a result of small imprecisions between the DEM-derived slopes and the exact location of glacier margins (Frey et al., 2014). This might result in a misleading detection of sometimes large overdeepenings and, thus, future lakes and needs to be carefully considered during the lake site selection procedure.

For the semiautomatic ranked confidence approach using a 5° slope threshold exclusion criterion and assignment of points for three additional glacier morphology criteria it is important to narrow down uncertainties related to the modeling as also confirmed in other studies (Colonia et al., 2017; Frey et al., 2010; Haeberli et al., 2016b). Another important discussion is the selection of the minimum lake area for GlabTop modeling. While we used a relatively small minimum of 2700 m², other studies set the threshold at a higher value between 10,000 m² (Colonia et al., 2017) and 20,000 m² (Kapitsa et al., 2017) in order to avoid artifacts in the modelling results. However, as outlined before, the multiple-criteria-selection protocol provides a fairly robust estimation of potential lake sites. At least three (five) out of 20 potential future lakes would have not been detected with the larger lake threshold of 10,000 m² (20,000 m²).

Additionally it should be mentioned, that overdeepenings modeled and selected by confidence-ranking are not per se sites for new lakes. While GlabTop quite robustly determines the approximated location (cf. Kapitsa et al., 2017), shape and size of the potential lakes are much more uncertain (Colonia et al., 2017). Sediment rates, especially of debris-covered glaciers, local future geomorphology (e. g. moraine drainage, breach, etc.) and potential lake bed topography are determinant (Colonia et al., 2017; Cook and Quincey, 2015; Linsbauer et al., 2016) but at the same time difficult to anticipate and include into the model.

5.3 Implications for future water management and perspectives

The estimated ice volume loss in the VUB between 1988 and 2016 is particularly impressive when converted into a tangible measure. A loss of 1.499 km³ of potable water (*Tab. 2*) would correspond to ~37 years of Cusco's water supply considering an average water demand of 250 l/d/capita and an urban population of 447,900 inhabitants (INEI, 2017b). With a future scenario assuming 1% annual population growth only (1,033,181 inhabitants in 2100) and unchanged water demand, potential water release from vanishing glaciers could be translated into a volume of ~30 years (RCP2.6: 2.820 km³) and 58 years (RCP8.5: 5.492 km³) to satisfy Cusco's water supply. At the same time, the potential increase in lake water volume of 0.062 km³ for 1988-2016 and additional 0.032 km³ (RCP2.6) or 0.041 km³ (RCP8.5) until 2100 do not at all outweigh the potential loss of fresh water from glacier melt runoff. Furthermore, while new and growing lakes do not per se contribute to the water supply in the region, plans for damming and regulating the lakes can raise serious social conflicts (Carey et al., 2012; Drenkhan et al., 2015)

At the same time, water demand in key sectors such as agriculture, housing and hydropower, is increasing in the region (Drenkhan et al., 2015) and, thus, exacerbating long-term pressure on water resources in the VUB, particularly in the dry season. This points out even more the urgent need for robust and integrative adaptation mechanisms. To address this challenge, a closer collaboration at the interface of science and policy is needed. Although the modelling of future lakes cannot directly be used to determine precise future volume for e. g. new hydropower and irrigation reservoirs, information on the potential lake locations, magnitude of change and storage options can support important planning and decision processes. Decision-makers, such as the local and regional governments as well as the regional water provider SEDACUSCO and hydropower operator EGEMSA could benefit from these estimations for further adaptation planning.

6. CONCLUSIONS

This study represents a first approach to comprehensively couple past, present and future glacier and lake development at basin scale under scenarios of climate change. Our analysis of current and potential future glacier shrinkage and lake growth draws a complex picture of non-uniform spatiotemporal change in the VUB. The following main messages can be distilled for this study:

- Glacier areas (volumes) have substantially decreased by 37% (21%) between 1988 and 2016.
- Adjacent lakes have increased in number (18%), area (16%) and volume (10%) over this period.
- Spatiotemporal variability, such as different rates of glacier shrinkage in the four different mountain ranges and temporary drying of lakes, challenges the analysis and understanding of the drivers of change.
- Future tropical Andean landscapes could be mostly glacier-free with some remaining glaciated peaks over ~6000 m asl. until 2100 and beyond (cf. Schauwecker et al., 2017). The amount of

GHG emitted in the future, and hence, the emission and temperature change scenarios, have a determinant influence on the magnitude and timing of future deglaciation and lake growth.

- A tipping point of strongest glacier volume loss and lake volume growth might be reached in the near-future (i. e. before 2050).
- Several challenges remain in the basin, among others, due to poor data availability and quality (cf. Salzmann et al., 2013), and as a consequence, limited understanding of complex hydroclimatic processes in an extreme topography and hence high uncertainty prevail, which is typical for the Andean region (Buytaert et al., 2017; Huggel et al., 2015).
- Options for long-term water management of new lakes must be analyzed now in close collaboration with local and regional decision makers at the interface of science and policy.

More research is needed to close several data gaps, tackle uncertainties and confirm some of the possible trends suggested here. We would like to encourage further research on this integrative topic to address water risks and future management options in the context of strong ongoing changes in the tropical Andes of Peru and elsewhere in glaciated high mountain regions.

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TABLE CAPTIONS

Table 1 Satellite imagery with NDSI, blue band cast and NDWI thresholds (1988-2016).

Table 2 Glacier area (A), ice volume (Vol) and water volume (W Vol) changes (1988-2016).

Table 3 Glacier area and volume changes (1988-2016) by cordilleras. VN = Cordillera Vilcanota, QC = Quelccaya ice cap, UB = Cordillera Urubamba and VB = Cordillera Vilcabamba. NWF = northwestern glacier fragment (UB + VB), SEF = southeastern glacier fragment (VN + QC).

Table 4 Glacier terminus (H_{min}) and approximated Equilibrium Line Altitude (H_{mean}) changes (1988-2016) by cordilleras und for the entire VUB.

Table 5 Lake area (A), volume (Vol) and number changes (1988-2016).

Table 6 Future glacier area (A), ice volume (Vol) and water volume (W Vol) extent according to the RCP2.6 and RCP8.5 scenarios and estimated temperature-dependent (Tavg) Freezing Line Heights (FLH) for 2050 and 2100.

Table 7 Future lake area (A), volume (Vol) and number extent according to the RCP2.6 and RCP8.5 scenario glacier extent for 2050 and 2100.

TABLES

Table 1

DATE	SENSOR	PATH/ROW	NDSI RANGE	BLUE BAND CAST RANGE	NDWI RANGE
1988 (02.08./25.08.)	Landsat 5 TM	04/69 03/70 04/70	0.31 – 0.33	35 – 46	A: -0.42 – -0.51 B: -0.51 – -0.65 C: -0.30
1998 (04.07./29.07./05.08.)			0.31 – 0.33	35 – 39	A: -0.43 – -0.46 B: -0.51 – -0.58 C: 0.19
2004 (11.06./18.06.)			0.30 – 0.43	31 – 32	A: -0.44 – -0.47 B: -0.60 C: -0.32
2010 (21.07./16.08./16.09.)			0.30 – 0.41	31 – 41	A: -0.36 – -0.51 B: -0.45 – -0.65 C: -0.24
2016 (22.07./29.07.)	Sentinel-2 MSI	T18LYL/T18LZK T18LZL T19LBD/T19LBE	0.65 – 0.80	500 – 700	A: -0.35 B: -0.44 C: 0.07

Table 2

YEAR	A (km²)	Vol (km³)	ΔA (%)	ΔA (%/year)	ΔVol (%)	ΔVol (%/year)	W Vol (km³)
1988	226.06	8.1223					7.3100
1998	188.36	7.6726	-16.68	-1.67	-5.54	-0.55	6.9054
2004	173.10	7.3387	-8.10	-1.35	-4.35	-0.73	6.6048
2010	152.50	6.8188	-11.90	-1.98	-7.08	-1.18	6.1369
2016	141.68	6.4568	-7.09	-1.18	-5.31	-0.88	5.8111
TOTAL	***-84.38***	***-1.6655***	***-37.33***	***-1.33***	***-20.51***	***-0.73***	***-1.4990***

Table 3

	YEAR	VN	QC	UB	VB	*SEF*	*NWF*
GLACIER AREA *(CHANGE)* km² *(%/year)*	*1988*	101.28	24.38	34.76	65.64	125.66	100.40
	1998	84.26 *(-1.68)*	22.28 *(-0.86)*	28.42 *(-1.83)*	53.40 *(-1.86)*	106.54 *(-1.52)*	81.82 *(-1.85)*
	2004	78.28 *(-1.18)*	21.04 *(-0.93)*	24.70 *(-2.18)*	49.08 *(-1.35)*	99.32 *(-1.13)*	73.78 *(-1.64)*
	2010	69.74 *(-1.82)*	19.60 *(-1.14)*	20.95 *(-2.53)*	42.21 *(-2.33)*	89.33 *(-1.68)*	63.17 *(-2.40)*
	2016	66.01 *(-0.89)*	18.39 *(-1.03)*	18.11 *(-2.26)*	39.13 *(-1.22)*	84.40 *(-0.92)*	57.24 *(-1.56)*
TOTAL		**-35.27 *(-1.24)***	**-5.99 *(-0.88)***	**-16.65 *(-1.71)***	**-26.51 *(-1.44)***	**-41.26 *(-1.17)***	**-43.16 *(-1.54)***
GLACIER VOLUME *(CHANGE)* km³ *(%/year)*	*1988*	4.2933	1.3754	0.8207	1.6312	5.6687	2.4519
	1998	4.0427 *(-0.58)*	1.3420 *(-0.24)*	0.7652 *(-0.68)*	1.5233 *(-0.66)*	5.3847 *(-0.50)*	2.2885 *(-0.67)*
	2004	3.8691 *(-0.72)*	1.2971 *(-0.56)*	0.7085 *(-1.23)*	1.4623 *(-0.67)*	5.1662 *(-0.68)*	2.1708 *(-0.86)*
	2010	3.6089 *(-1.12)*	1.2423 *(-0.70)*	0.6334 *(-1.77)*	1.3329 *(-1.47)*	4.8513 *(-1.02)*	1.9663 *(-1.57)*
	2016	3.4626 *(-0.68)*	1.1863 *(-0.75)*	0.5526 *(-2.13)*	1.2543 *(-0.98)*	4.6489 *(-0.70)*	1.8069 *(-1.35)*
TOTAL		**-0.8307 *(-0.75)***	**-0.1891 *(-0.52)***	**-0.2681 *(-1.34)***	**-0.3769 *(-0.91)***	**-1.0198 *(-0.63)***	**-0.6450 *(-1.12)***

Table 4

YEAR	1988		1998		2004		2010		2016	
	H_{min}	H_{mean}	H_{min}	H_{mean}	H_{min}	H_{mean}	H_{min}	H_{mean}	H_{min}	H_{mean}
VN	5124	5354	5151	5365	5169	5373	5198	5386	5214	5399
QC	5126	5352	5148	5363	5180	5379	5210	5394	5240	5409
UB	4739	5027	4788	5050	4823	5065	4861	5080	4906	5108
VB	4722	5039	4772	5062	4801	5075	4848	5099	4865	5109
VUB	4889	5163	4929	5181	4956	5194	4994	5211	5017	5226
Difference (m)			***40***	***18***	***27***	***13***	***38***	***17***	***23***	***15***
Annual change (%)			***0.08***	***0.04***	***0.09***	***0.04***	***0.13***	***0.06***	***0.08***	***0.05***

Table 5

YEAR	A (km²)	Vol (km³)	ΔA (%)	ΔA (%/year)	ΔVol (%)	ΔVol (%/year)	Lakes (No.)	ΔLakes (%)	ΔLakes (%/year)
1988	23.28	0.6371					460		
1998	23.17	0.6146	-0.48	-0.05	-3.53	-0.35	458	-0.43	-0.04
2004	23.66	0.6265	2.09	0.35	1.93	0.32	495	8.08	1.35
2010	24.83	0.6651	4.94	0.82	6.17	1.03	497	0.40	0.07
2016	26.90	0.6991	8.36	1.39	5.10	0.85	544	9.46	1.58
TOTAL	***3.62***	***0.0620***	***15.54***	***0.55***	***9.73***	***0.35***	***84***	***18.26***	***0.65***

Table 6

PERIOD	Scenario	Tavg	ΔFLH (m)	FLH (m asl.)	A (km²)	Vol (km³)	ΔA (%)	ΔA (%/year)	ΔVol (%)	ΔVol (%/year)	W Vol (km³)
2050	**RCP2.6**	12.9	176	5276	83.97	3.7712	-40.73	-1.20	-41.59	-1.22	3.0169
	RCP8.5	13.1	297	5307	78.00	3.5480	-44.94	-1.32	-45.05	-1.33	2.8384
$TOTAL_{RCP2.6}$ 1988-2050					***-142.09***	***-4.3511***	***-62.86***	***-1.85***	***-53.57***	***-1.58***	***-4.2931***
$TOTAL_{RCP8.5}$ 1988-2050					***-148.06***	***-4.5743***	***-65.49***	***-1.93***	***-56.32***	***-1.66***	***-4.4717***
2100	**RCP2.6**	12.9	181	5281	83.05	3.7386	-41.38	-0.49	-42.10	-0.50	2.9909
	RCP8.5	15.4	637	5647	10.31	0.3986	-92.72	-1.10	-93.83	-1.12	0.3189
$TOTAL_{RCP2.6}$ 1988-2100					***-143.01***	***-4.3836***	***-63.26***	***-0.75***	***-53.97***	***-0.64***	***-4.3191***

TOTAL$_{RCP8.5}$ 1988-2100	***-215.75***	***-7.7236***	***-95.44***	***-1.14***	***-95.09***	***-1.13***	***-6.9911***

All T_{avg} and FLH values refer to the baseline (1981-2010) with RCP2.6 (11.7°C, 5100 m asl.) and RCP8.5 (11.1°C, 5010 m asl.), respectively.

Table 7

PERIOD	Scenario	A (km²)	Vol (km³)	ΔA (%)	ΔA (%/year)	ΔVol (%)	ΔVol (%/year)	Lakes (No.)	ΔLakes (%)	ΔLakes (%/year)
2050	**RCP2.6**	27.76	0.7315	3.20	0.09	4.64	0.14	558	2.57	0.08
	RCP8.5	27.98	0.7359	4.03	0.12	5.26	0.15	560	2.94	0.09
TOTAL$_{RCP2.6}$ 1988-2050		***4.48***	***0.0944***	***19.23***	***0.57***	***14.82***	***0.44***	***98***	***21.30***	***0.63***
TOTAL$_{RCP8.5}$ 1988-2050		***4.70***	***0.0988***	***20.19***	***0.59***	***15.50***	***0.46***	***100***	***21.74***	***0.64***
2100	**RCP2.6**	27.76	0.7315	3.20	0.04	4.64	0.06	558	2.57	0.03
	RCP8.5	28.53	0.7405	6.04	0.07	5.92	0.07	564	3.68	0.04
TOTAL$_{RCP2.6}$ 1988-2100		***4.48***	***0.0944***	***19.23***	***0.57***	***14.82***	***0.44***	***98***	***21.30***	***0.63***
TOTAL$_{RCP8.5}$ 1988-2100		***5.24***	***0.1034***	***22.51***	***0.66***	***16.23***	***0.48***	***104***	***22.61***	***0.66***

FIGURE CAPTIONS

Fig. 0 (*graphical abstract*) Past, present and potential future changes of glacier and lake extent in the VUB. Left image: past and present glacier outlines for 1988 (orange), 2004 (green) and 2016 (blue) and current lakes (dark blue). Right image: future glacier outlines for 2100 (RCP2.6 and RC8.5) with possible future lakes (light blue). Central image: photography in Cordillera Vilcanota taken in 08/2016. Base imagery: Sentinel-2 (2016) and SRTM (AP 12.5 m) for an extract of the Cordillera Vilcanota.

Fig. 1 Overview of the Vilcanota-Urubamba-Vilcabamba basin (VUB) situated in Peru (rectangle in the small overview map) with main cities (red circles), prominent glaciers (turquoise triangles) and two principal reservoirs (Sibinacocha and Langui Loy). Glaciers belonging to the VUB (dashed pink delimitation) are highlighted as turquoise area. NWF = northwestern glacier fragment, SEF = southeastern glacier fragment.

Fig. 2 a: Glacier shrinkage rates for all four intervals in the study period (1988-2016) by cordilleras and for the entire VUB. In brackets: mean annual shrinkage rate for the whole period 1988-2016.

Fig. 2 b: Minimum (H_{min}) and mean (H_{mean}) glacier altitude change for 1988 (solid line) and 2016 (dashed line) by cordilleras and for the entire VUB. In brackets: mean maximum (H_{max}) glacier altitude for 2016.

Fig. 3 Glacier (turquoise) and lake (dark blue) area change rates (1988-2016).

Fig. 4 Number of lakes by four altitudinal levels and area classes (1988-2016). Each horizontal group of lines indicates the number and altitudinal levels ordered by five study years with the bottom (top) line representing 1988 (2016).

Fig. 5 Current and future extent of glaciers and lakes (2016-2050-2100) with examples from Cordillera Vilcanota (1, red boxes) and Quelccaya ice cap (2, orange boxes). Current glacier areas of the VUB are indicates in turquoise, future glacier extent in red colors. Current lake areas are drawn in dark blue, future lakes in light blue. a: Distribution of future glacier extent until 2050 (small box, green colours) and 2100 (red colours) under the RCP2.6 and RCP8.5 scenarios. b: Distribution of potential future lakes and ice thickness indicating the modeling of overdeepenings related to shape factor selection (f = 0.65, 0.80 or 0.90).

FIGURES

Figure 0

Figure 1

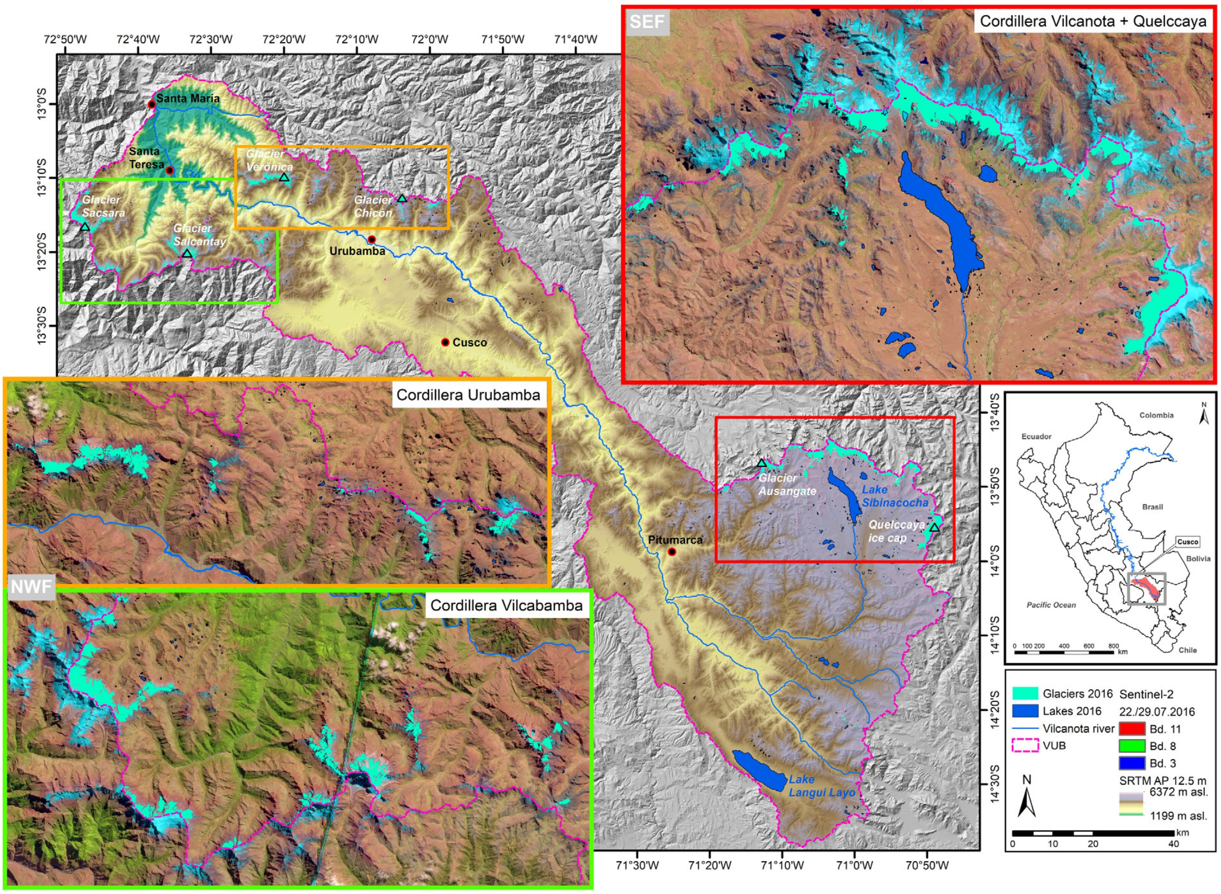
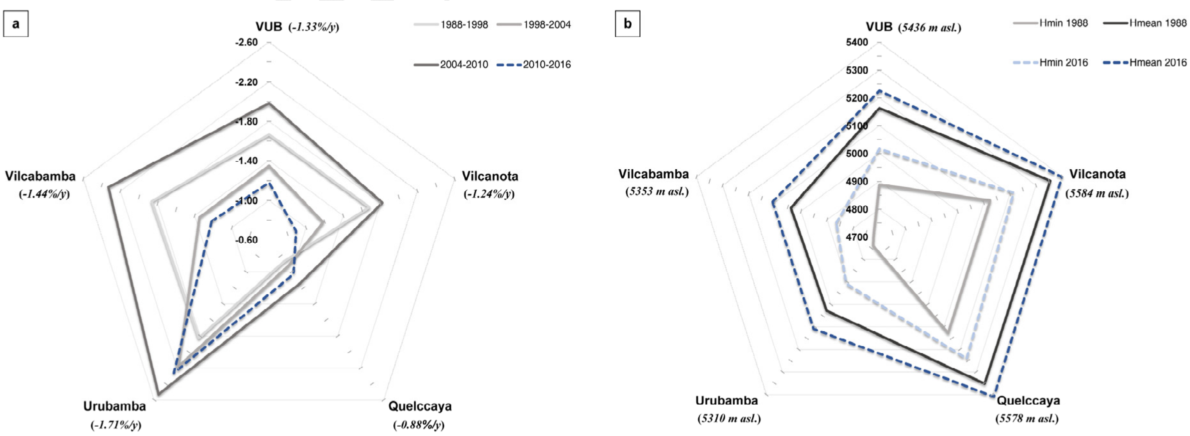


Figure 2



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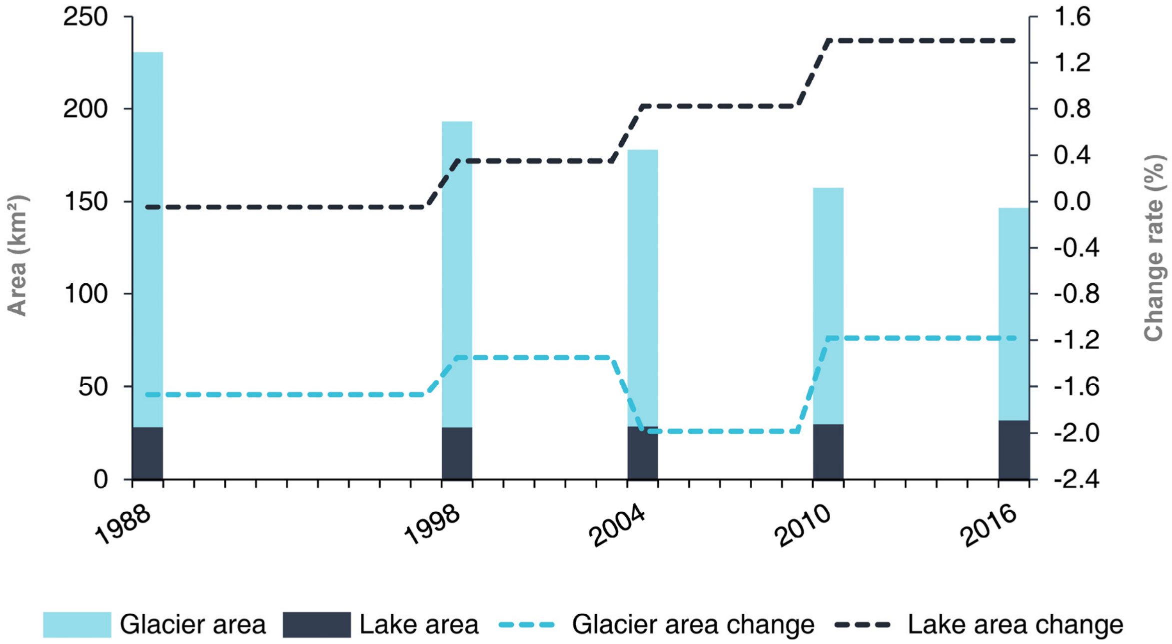

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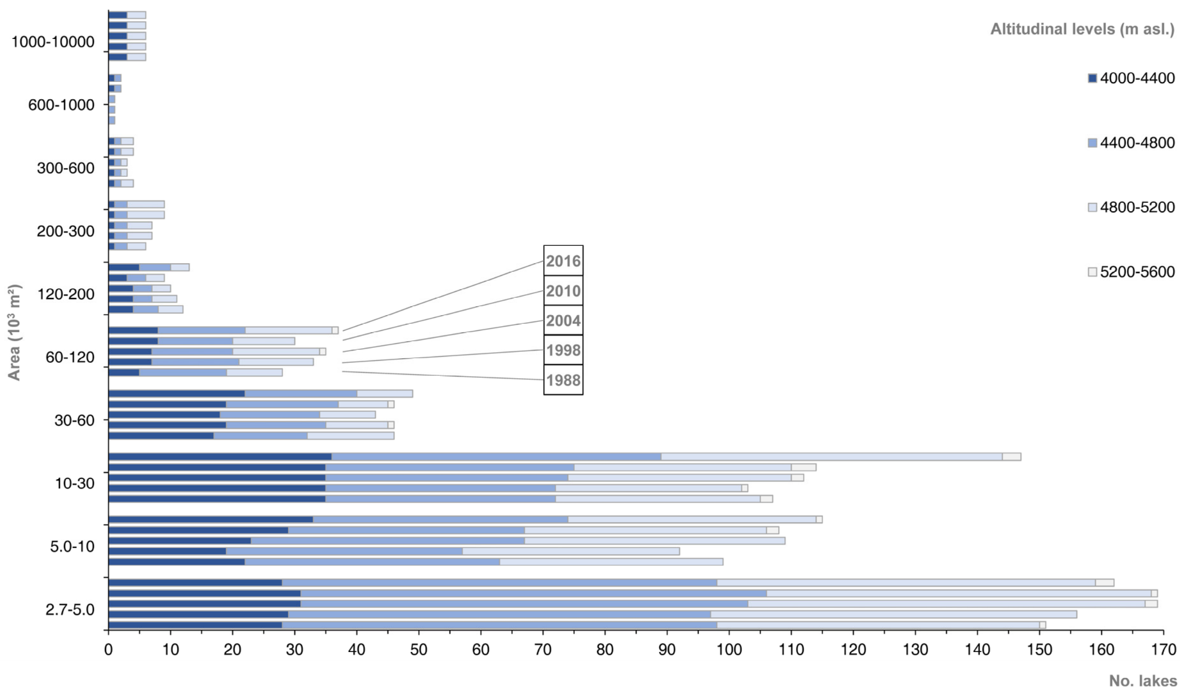
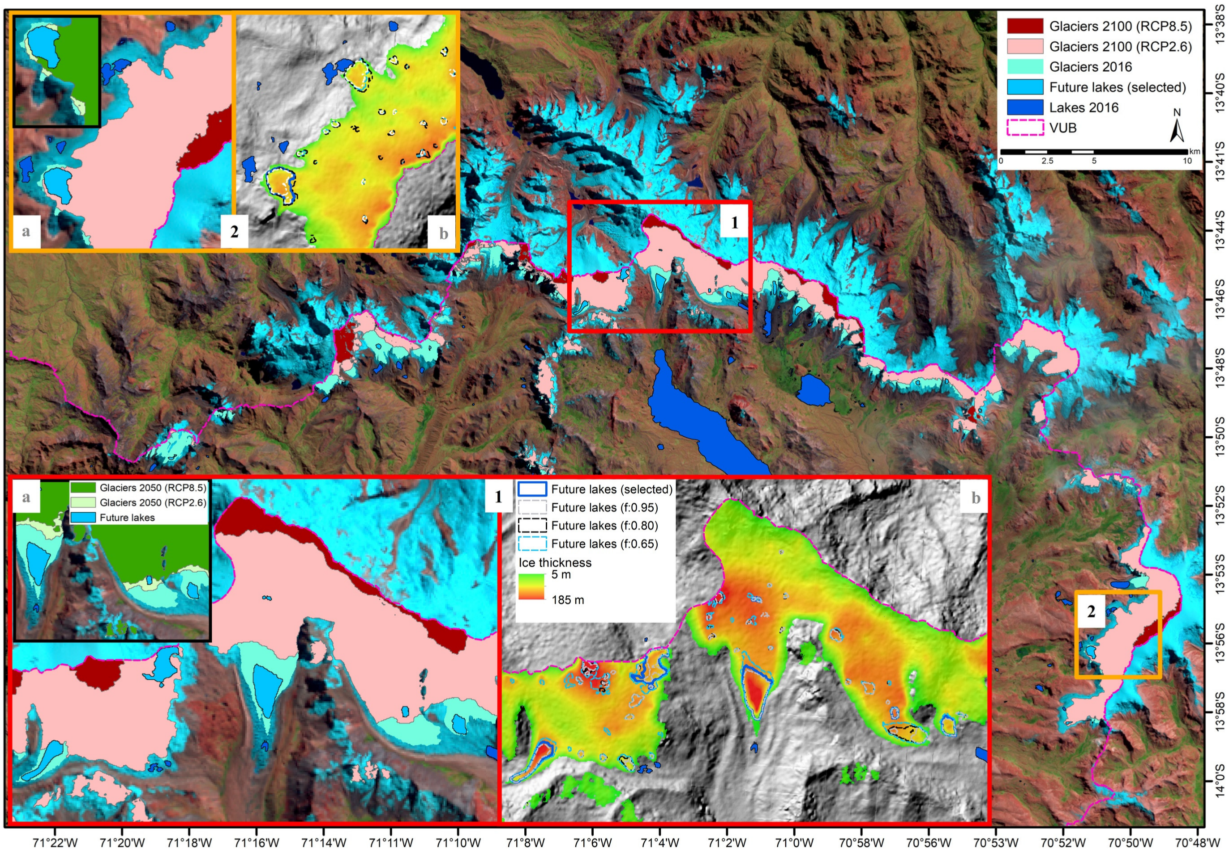


Figure 5


Glaciers 2100 (RCP8.5)
Glaciers 2100 (RCP2.6)
Glaciers 2016
Future lakes (selected)
Lakes 2016
VUB
N
0 2.5 5 10 km
1
2
a
b
Glaciers 2050 (RCP8.5)
Glaciers 2050 (RCP2.6)
Future lakes
Future lakes (selected)
Future lakes (f:0.95)
Future lakes (f:0.80)
Future lakes (f:0.65)
Ice thickness
5 m
185 m
71°22'W 71°20'W 71°18'W 71°16'W 71°14'W 71°11'W 71°10'W 71°8'W 71°6'W 71°4'W 71°2'W 71°0'W 70°58'W 70°56'W 70°53'W 70°52'W 70°50'W 70°48'W
13°38'S 13°40'S 13°41'S 13°44'S 13°46'S 13°48'S 13°50'S 13°52'S 13°53'S 13°56'S 13°58'S 14°0'S